Effects of γ-ray radiation on magnetic properties of NdFeB and SmCo permanent magnets for space applications.

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***Abstract*–Several samples of NdFeB and SmCo permanent magnets have been irradiated with gamma rays up to different total irradiation doses until 1Mrad(Si). Magnetic properties of the samples have been measured at different temperatures before and after irradiation. The modifications of the magnetic parameters are presented. From these results it is highlighted which permanent magnets show more resistance to radiation and are more suitable to be included in devices for space applications or high radiation environments.**

I. Introduction

COMMON applications of permanent magnets (PMs) on space are in magnetic cleanliness, offsetting magnetic fields next to magnetic sensors, encoders, dust collectors on board rovers, non-contact switches, etc. Among all magnets, NdFB and SmCo PMs are widely used in military and space sectors because of their high remnant magnetization and high stability in wide temperature swings. However, the effects of extreme radiation conditions on them in long-term and deep space missions are not so well studied.

In the frame of the Space Infrared Telescope for Cosmology and Astrophysics (SPICA) mission, a magnetic encoder to discern between different positions of a filter wheel has been developed for SAFARI Bread Board (BB) instrument, a 30-200μm imaging spectrometer. This magnetic encoder is based on the different magnetic signature in the position of a magnetometer of distinct configurations of permanent magnets [1]. Besides, these materials are currently considered to be used in the design of a MEMS-based magnetic susceptometer developed in the Space Magnetism Laboratory at INTA [2] within the frame of TITANO project.

NdFeB and SmCo permanent magnets have been submitted to a γ-ray radiation test, in order to determine their stability under high doses of gamma radiation and the suitability of these materials for space applications.

Though the effects of radiation on magnetic properties of permanent magnets have been studied before in several works [3], [4], the question concerning small changes on remnant magnetization is not so well understood, which could cause miscalculation in the SAFARI encoder and similar devices.

The samples chosen for the test were commercial permanent magnets by HKMC Engineering from the same batch:

- NdFeB 3mm Ø x 3mm height
- SmCo 4mm Ø x 2mm height

II. Radiation Test

In this test, 18 magnets divided in three different sets have been irradiated in November 2013 at the Radiophysics Laboratory, Universidad de Santiago de Compostela (USC), Spain, with a ^{60}Co source.

Different sets of samples were irradiated to distinct total irradiation dose (TID), namely 30 krad(Si), 170 krad(Si) and 800 krad(Si), at a dose rate of 23 Krad/h in order to study progressive damage.

Therefore the magnets were subdivided in sets of three magnets per composition. Each of the three magnets will be characterized at a selected temperature in such a way that the magnetization versus temperature curves are well represented (Table I).

Magnetic properties are measured at the selected temperature for each magnet prior and after the test.

III. Experimental Procedure

The measurements of the magnetic characteristics have been carried out in the VSM facility at Space Magnetism Laboratory of INTA (Spain). This study was performed comparing the magnetic moment of the magnets before and after the radiation test. Measurements of the moment as a function of the angle were taken starting from the magnetization axis parallel to the measurement direction and rotating the sample, maintaining the magnetization axis perpendicular to the measurement plane.

The measurements were performed positioning the magnet with its magnetic moment direction (magnetization axis) parallel to the magnetization axis of the VSM facility and axis probe, ensuring optimum sensitivity in the maximum magnetization direction of the magnet. The sample was rotated 360º characterizing parallel, perpendicular and magnitude magnetization.

This procedure was repeated for each sample at a representative range of temperatures, which is a tradeoff between temperatures lower than their Curie temperature (TC) to maintain the magnetic order (Figure 1), and a swing that covers the needs of most common Solar System space missions.

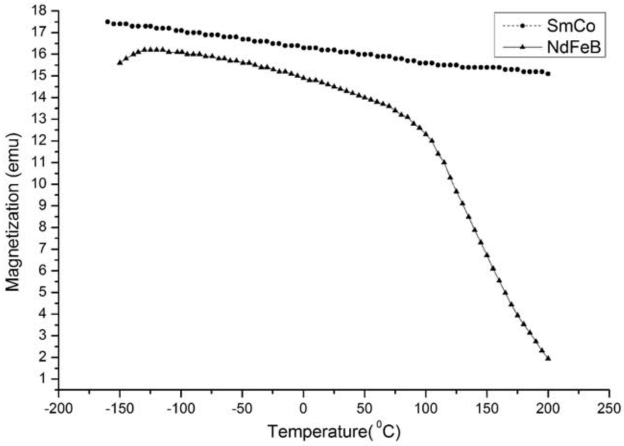

Figure 1. Experimental magnetization versus temperature curves for NdFeB and SmCo.

Temperatures of -100 and 25 ºC are common for both materials. High temperature chosen for NdFeB (TC = 120 ºC) was 100 ºC, and 225 ºC for SmCo (TC = 350 ºC). The test guarantees repeatability, and is non-destructive excepted for the high temperature measurement of NdFeB since thermal demagnetization occurs.

IV. RESULTS AND DISCUSSION

Figure 2 and Figure 3 show relative changes on the maximum magnetization magnitude as a function of the different doses at the different temperatures:

$$\text{Normalized } \Delta M = \frac{\text{After-test magnetization}}{\text{Initial magnetization}} - 1$$

Table II depicts the initial values of the maximum magnetic moment for the studied permanent magnets before irradiation. Results show for both materials that this difference is higher at lower temperatures, decreasing with the increase of temperature and showing at the maximum studied temperature that the remnant magnetization before and after irradiation is almost the same.

Previous investigations on the effects of gamma and neutron radiation on Neodymium or Cobalt based permanent magnets typically demonstrate deterioration of magnetic properties [5] and changes in crystal structure [6].

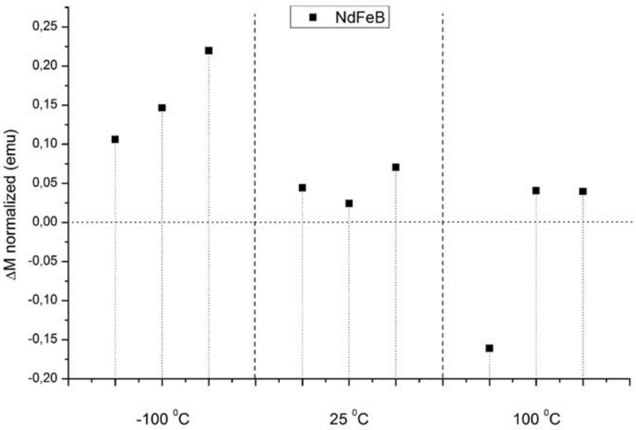

Figure 2. Changes on remnant magnetization of NdFeB magnets at different temperatures and TID.

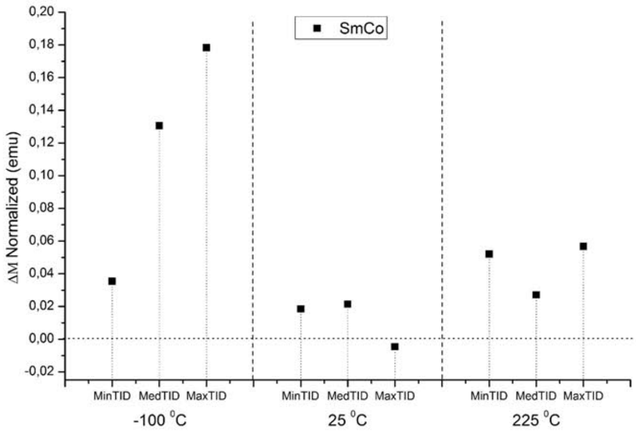

Figure 3. Changes on remnant magnetization of SmCo magnets at different temperatures and TID.

In contrast, results achieved during this test show that the magnetic moment tends to increase after irradiation in 88% of the samples and decreases in the rest. Even though the variation in the magnetic moment is very weak and it is in the limit of our resolution, the trend could suggest a mechanism that modifies structural and non-structural magnetic properties favoring net magnetization.

Three hypothesis have been taken into account:

1. Local thermal annealing: The studied magnets are sintered from a stoichiometric mix of compounds. Though the expected material generated by a sintering process has an amorphous structure, the high pressures and temperatures reached during the process cause spontaneous formation of isolated crystals. The magnet has a net magnetization in one direction, but this is the contribution of all the magnetic domains of the material, which one is not oriented in the same direction. Due to its high coercitivity and stability, the domains of these magnets remain magnetized on its direction even under high values of external magnetic field and great ranges of temperature. Under a local high enough increase of temperature in a localized region, the volume in the presence of the magnetic field of nearby domains can

experience a strain, which changes the moment by magnetostrictive effect or even recrystallize a small volume in the presence of the neighboring field. Once the temperature is lowered the domains conserve their new orientation, generating a higher value of the remnant magnetization. During the post-irradiation VSM measurement, samples that are studied at low temperatures present different magnetization meanwhile at high temperatures this remagnetization disappears due to the higher mobility of the orientation of the magnetic domains, disappearing the effect mentioned above. Same process may happen also for domains with anti-ferromagnetic interaction producing a decrease on the net magnetization. Spontaneous concentration of γ-ray during the test can cause this increase of temperature, justifying the obtained response.

2. Defects diffusion: Mechanism proposed above is activated by temperature, and the expected changes in temperature during the test are not high enough for recrystallization. The irradiation facility used at USC has homogeneity better than 5%, what decreases the probability of spontaneous concentration of γ-rays. Nevertheless, point defects move by diffusion processes which are activated at lower temperatures. Radiation-induce thermal effects on creation and diffusion of defects may play a role on the observed changes on the magnetization, due to the volume changes and magnetostriction effects, and magnetic properties of the defects. However, previous studies suggest that defect formation induced by γ-ray irradiation is very small [6].

3. Compton effect: Elastic collision between photons and electrons in outer shells may produce changes in the ordering of magnetic moments by affecting the spin of atoms with magnetic phase. As it suggested by R.S. Gao [5], these collisions, may cause changes in the moving direction of electronic orbitals. This effect disappears under a thermal process or during remagnetization, suggesting that the studied accumulated doses of γ-ray do not produce recrystallization or changes in the structure. This hypothesis avoid appealing to radiation-induce thermal effects, what fits the expected negligible increase of temperature during the irradiation test and the recovery of magnetic properties in the high temperatures post-irradiation characterization.

V. CONCLUSSIONS

A set of NdFeB and SmCo PMs have been irradiated with gamma rays at different doses to study the changes of their magnetic moment with radiation along a wide swing of temperature (-100 to 225 ºC).

In principle, NdFeB PMs exhibit lower stability with temperature (Figure 1) than SmCo ones, presenting a critical temperature around 100ºC where magnetization abruptly decreases with temperature (Curie temperature around 120º C according with the manufacturer). On the other hand, SmCo PMs presents a linear behavior with small decreases on its remnant magnetization, proving high stability and a high value of its Curie temperature (around 350º C according with the manufacturer).

Obtained results show weak variations in the magnetic properties of irradiated PMs along the studied temperatures. NdFeB and SmCo PMs seem to be stable and show changes in their magnetic moment lower than the 5 % in 70 % of the cases of study after the irradiation.

The obtained results corroborate previous observations [7],[8], which state that SmCo PMs have higher resistance to gamma radiation than NdFeB PMs.

However, further experiments should be performed with a set up with better resolution and a wider sample of PMs for a better understanding of the observed changes.

To summarize, the higher thermal stability and radiation resistance of Samarium–Cobalt based permanent magnets prove its suitability for space applications rather than Neodymium–Iron–Boron. In particular it is proven their suitability for the magnetic encoder in SPICA's instrument and in the magnetic MEMS - susceptometer.

VI. ACKNOWLEDGMENT

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TABLE I
TEMPERATURE OF CHARACTERIZATION OF THE SAMPLES

	Min TID (30 Krad)			**Med TID (170 Krad)**			**Max TID (800 Krad)**		
NdFeB	-100ºC	25ºC	100ºC	-100ºC	25ºC	100ºC	-100ºC	25ºC	100ºC
SmCo	-100 ºC	25ºC	225ºC	-100ºC	25ºC	225ºC	-100ºC	25ºC	225ºC

TABLE II
INITIAL VALUE OF THE MAGNETIC MOMENT OF THE SAMPLES

		Min TID				**Med TID**				**Max TID**			
Temperature (ºC)		-100	25	100	225	-100	25	100	225	-100	25	100	225
M (emu)	NdFeB	16.4	14.2	13.1	X	16.6	15.3	14.3	X	16.6	14.9	12.9	X
	SmCo	17.4	14.9	X	14.4	15.6	15.3	X	14.2	16.2	15	X	13.5